Multiband enhanced absorption of monolayer graphene with attenuated total reflectance configuration and sensing application

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2017 Appl. Phys. Express 10 015102
(http://iopscience.iop.org/1882-0786/10/1/015102)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 58.192.116.66
This content was downloaded on 14/12/2016 at 12:15

Please note that terms and conditions apply.
Multiband enhanced absorption of monolayer graphene with attenuated total reflection configuration and sensing application

Nan Wang¹, Lingbing Bu¹*, Yunyun Chen²,³, Gaige Zheng²,³*, Xiujuan Zou², Linhua Xu², and Jicheng Wang⁴

¹Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044, China
²School of Physics and Optoelectronic Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China
³Jiangsu Collaborative Innovation Center on Atmospheric Environment and Equipment Technology (CICAAET), Nanjing University of Information Science and Technology, Nanjing 210044, China
⁴School of Science, Optoelectronic Engineering and Technology Research Center, Jiangnan University, Wuxi 214122, China

Abstract

An enhanced absorption of monolayer graphene is obtained in a multilayer film-based attenuated total reflection configuration in the visible wavelength range. The enhanced absorption under transverse magnetic and electric conditions is associated with the excitation of the waveguide mode in the thin-film layer, which is verified by the numerical calculation of field profiles. The obtained results manifest that the model induces a high field enhancement at the graphene–dielectric interface with the resonant angle, which implies potential sensing applications. The magnitude of the figure of merit is found to be three times higher than that of a conventional surface plasmon sensor.

© 2017 The Japan Society of Applied Physics

The attenuated total reflection (ATR) geometry usually consists of a glass prism with a thin metal layer deposited on one face of the prism and placed in contact with the medium to be probed, which is diffusely used as an optical method for surface plasmon (SP) excitation. Recently, the ATR structure has been used to excite graphene surface plasmon polaritons (SPPs) in the far-infrared (far-IR) wavelength range, and it was feasible to achieve sharp resonances of the attenuation of an EM wave. In the mid-infrared (mid-IR) to terahertz (THz) regions, graphene can sustain strong SPPs with an extremely strong confinement of fields to the interface, which leads to a strong light–graphene interaction together with a nearly 100% absorption at the resonant wavelength. Together with the ability of tuning the chemical potential by an external gate, making this system particularly interesting, the formation of surface waves can be controlled externally. However, in the visible (Vis) and near-infrared (near-IR) regions, the interband transitions of electrons dominate the optical response of graphene, whose conductivity is purely a real quantity. In this case, monolayer graphene has a weak optical absorption of 2.3% of incident light, which is beneficial for devices such as LCD screens, transparent electrodes in solar cells, and organic light-emitting diodes. Pirruccio et al. have experimentally demonstrated a broadband enhancement of light absorption by graphene at Vis wavelengths by using an ATR configuration with a multilayer structure. The absorption could be increased to 60 and 70% for 5 and 10 layers of graphene, respectively.

In this paper, we propose another possible operation principle for a graphene-based absorber through the resonant coupling of the external EM radiation in an ATR structure, which is schematically shown in Fig. 1(a). Our work focuses on the Vis spectrum where graphene exhibits a dielectric behavior and does not support SPs. The ATR prevents light from being scattered in the transmission far field for angles of incidence larger than the critical angle (θc). The findings provide insight regarding how nanostructured multilayer films affect the absorption of graphene in the Vis wavelength range. In addition, we evaluate some of the new features found in the absorption spectrum and find that they may be more sensitive when used as biosensors.

Fig. 1. (a) Schematic representation of the method used to enhance the absorption of monolayer graphene. On top of a prism with the relative permittivity εp, there is a dielectric layer with the permittivity ε1 (of width t₁). Another dielectric layer (dielectric 2) with the relative permittivity ε2 (of width t₂) is sandwiched between graphene and dielectric 1. The incident angle of the incoming light is θi. (b) Absorption of EM waves with different polarization states versus incident angle. The parameters are chosen as εp = 1.7, ε₁ = 1.34, ε₂ = 1.464, t₁ = 0.635 μm, t₂ = 1.5 μm, and d = 0.34 nm.

Figure 1(a) illustrates the basic structure established in this work, consisting of a high-index prism (with the relative permittivity εp), which is used to increase the momentum of incident photons. A linearly polarized EM wave with a wavelength of λ₀ = 0.633 μm impinges on the prism, and while a dielectric layer is sandwiched between the prism and
A capping layer (with the relative permittivity \(\varepsilon_2\)), monolayer graphene is prepared on top of the whole structure. In order to facilitate the discussion of the problem, all dielectric constants are assumed real. Graphene is modeled as a thin dielectric layer with the permittivity expressed as 
\[ \varepsilon_g = 1 + i\sigma_g/\omega\varepsilon_0\varepsilon, \]
where \(d_g = 0.34\) nm is the graphene monolayer thickness, \(\omega\) represents the angular frequency, \(\varepsilon_0\) is the vacuum permittivity, and \(\sigma_g\) indicates the graphene surface conductivity. The frequency-dependent surface conductivity can be expressed as the sum of two terms: 
\[ \sigma_g = \sigma_{\text{intra}} + \sigma_{\text{inter}}. \]
The first term that corresponds to intraband electron-photon scattering can be described as \(17\)
\[ \sigma_{\text{intra}} = i\frac{e^2k_BT}{\pi(\omega + i\tau_1^{-1})} \left[ \frac{\mu_e}{k_BT} + 2\ln \left( \exp \left( -\frac{\mu_e}{k_BT} \right) + 1 \right) \right], \]
where \(e\) and \(\mu_e\) are the electron charge and chemical potential (equal to the Fermi level shift), respectively. \(k_B\) and \(h\) indicate the Boltzmann and reduced Planck constants, respectively, \(T\) is the temperature, and \(\tau\) stands for the momentum relaxation time due to charge carrier scattering. The physical parameters of graphene are set as \(\mu_e = 0.15\) eV, \(T = 300\) K, and \(\tau = 0.5\) ps. \(18\)

The key point in our design is to shine light on the prism at an angle larger than \(\theta_i\) for total internal reflection (TIR). From Snell’s law, it should have \(\sin\theta_i = \max(\varepsilon_1, \varepsilon_2)/\varepsilon_p\), and \(\theta_i\) can be smaller while choosing a larger \(\varepsilon_p\), which allows a broad range of angles (\(\theta_i < \theta < \pi/2\)) to be scanned. If the angle of incidence is larger than \(\theta_i\), the EM wave in the thin films between the prism and graphene will be evanescent in the \(z\)-direction. Since graphene is at a finite distance \(t_1 + t_2\) from the reflecting interface, it is possible to transfer the energy of the incoming light to the waveguide mode (WGM) via a frustrated TIR when the WG is located at a distance much larger than the decay length. \(19\)

In order to obtain absorption spectra, we need to solve the equations that result from the ordinary boundary conditions that the fields satisfy at each interface. Since the system is uniform in the \(y\)-direction, we can decompose the EM fields \(E^\text{(m)}\) and \(H^\text{(m)}\) into two components while considering the TE- and TM-polarized waves separately. For the TM-polarized wave, the magnetic field vector is perpendicular to the plane of incidence (xz) and we have \(E^\text{(m)} = (E^\text{(m)}_x, 0, E^\text{(m)}_z), H^\text{(m)} = (0, H^\text{(m)}_x, 0)\). For the TE-polarized wave, the magnetic field vector lies in the plane of incidence, \(E^\text{(m)} = (0, E^\text{(m)}_y, 0), H^\text{(m)} = (H^\text{(m)}_y, 0, H^\text{(m)}_z)\). According to the Maxwell equation \(\nabla \times H^\text{(m)} = -i\omega \mu_0 \sigma_e E^\text{(m)}\), the expressions of EM fields for different regions can be derived. Matching these boundary conditions, we can obtain explicit expressions for \(R\) and \(T\). The absorption \(A\) can be obtained through \(A = 1 - R - T\). The numerical analysis can be carried out by the rigorous coupled wave analysis (RCWA) method. \(20,21\)

The influences of the geometric parameters \(t_1\) and \(t_2\) on a monolayer graphene’s absorption are investigated and plotted in Fig. 2. The contour plots obtained from the results of RCWA exhibit multiple bright bands, indicating absorption enhancement. It is observed in Figs. 2(a) and 2(b) that the full width at half maximum (FWHM) of the absorption spectra decreases when \(t_1\) increases. Triple maximum absorption areas can be achieved within 50 to 60° when \(t_2\) is fixed at 1.5 \(\mu\)m. Absorption spectra versus \(t_2\) are depicted in Figs. 2(c) and 2(d). It is interesting to find that higher-order WGMs occur for a larger \(t_2\); thus, a multiple absorption band can be realized, as shown in the figures. It has been concluded that there is no plasmonic response in homogeneous undoped graphene, which is not suitable for absorption in the Vis range, \(20-22\) so the nearly 100% absorption is entirely controlled by the properties of the ATR and WGM.

Many reports have shown that SPs have the potential to improve light absorption in graphene owing to the near-field enhancement and high confinement of EM waves. One way to generate such a strong field is to place graphene at the vicinity of nanoantennas. \(23\) The other way is to utilize localized polaritons in metal gratings and metamaterials, which can also boost the absorptance of monolayer graphene. \(21,24\) However, the highly effective improvement of graphene absorption in all-dielectric systems is still rare and in urgent demand for functional design, especially in the Vis range.

To further clarify the origin of the enhanced absorption, the magnetic field (\(H_f\)) profiles inside the structure are calculated. The \(H\)-field distribution of the ATR structure is calculated at different angles at a wavelength of 633 nm under TM polarization, and the results obtained for \(\varepsilon_p = 1.7, \varepsilon_1 = 1.34, \varepsilon_2 = 1.464, t_2 = 1.5 \mu\)m, and \(d = 0.34\) nm are presented in Fig. 3. In the figures, the field enhancement factor, which is defined as the ratio of the absolute of the magnetic field amplitude to that of the incident light, is plotted as a function of the distance \(z\). It is clear that strong magnetic fields concentrate within a certain region for all three peaks. Figure 3(a) is obtained with \(\theta_{\text{in}} = 52.772°\), which indicates the minimum of the absorption peak in Fig. 1(b). Moreover, Fig. 3(b) is obtained with \(\theta_{\text{in}} = 56.016°\), which corresponds to the middle of the absorption peak in Fig. 1(b). Figure 3(c) is obtained with \(\theta_{\text{in}} = 58.216°\), and the red lines in the inset of the figures represent the position of
monolayer graphene, while the field enhancement factors are calculated as 4.751, 7.16, 6.366, and 0.185. In Figs. 3(a)–3(c), it is important to note that the magnetic field profile of the typical WGM is generated. It should also be noted that the field enhancement factors at the WG-graphene interfaces are as high as ~7. For comparison, the field profile with $\theta_{in} = 55^\circ$ is presented in Fig. 3(d). The field enhancement factor is plotted as a function of the distance $z$ on the left panel of each figure.

Fig. 3. (a)–(c) The distributions of the magnetic field $|H_y|$ at the incident angles correspond to the three absorption peaks as shown in Fig. 1(b). (d) Field profile with $\theta_{in} = 55^\circ$. The TM-polarized light with a wavelength of 0.633 µm is assumed to be incident on the structure. The other parameters are the same as those in Fig. 1(b). The field enhancement factor is plotted as a function of the distance $z$ on the left panel of each figure.

Fig. 4. Absorption maps of the graphene absorber versus the angle of incidence and wavelength for (a) TE- and (b) TM-polarized incident fields for the structure in Fig. 1(a).

Up to now, only the response of the optical absorbers at a wavelength of 0.633 µm is considered. It is also interesting to investigate the wavelength-dependent behavior. Figure 4 shows the absorption map obtained when the incident angle is varied in the range of 50–60° and the wavelength is varied in the range of 0.4–0.8 µm. By inspecting the plot, multiband enhanced absorption can be achieved, and it is evident that the absorption peak moves to larger angles with increasing incident wavelength.

Furthermore, in exactly the same manner as the conventional Kretschmann SPR system, the present structure can be used as a sensor. In bulk sensing, changes in the RI of dielectric 3 caused by the dissolution of analytes are detected by monitoring the changes in resonance curves. In thin-film sensing, changes in the RI and thickness of the thin film or molecular layers deposited onto the graphene surface are detected. It is of great interest to examine bulk sensing and the shift of the resonance angle caused by the change in the RI of dielectric 3. To realize this, we add a 50 nm film above the monolayer graphene, as might occur in a biological sensing system. Then, the reflectance for the structure with dielectric 3 changes from 1.332 to 1.336 with steps of $\Delta n = 0.001$.

Fig. 5. Proposal of the sensor using the multilayer thin films by using an attenuated total reflectance configuration. (b) Shift of the reflective spectra for the structure with $\epsilon_0 = 1.7$, $\epsilon_1 = 1.34$, $\epsilon_2 = 1.464$, $t_1 = 0.635\mu m$, $t_2 = 0.5\mu m$, and $d = 0.34\text{ nm}$. The RI of dielectric 3 changes from 1.332 to 1.336 with steps of $\Delta n = 0.001$.

As represented, the reflectivity curve shifts to higher angles when the RI is increased. The variation of the resonance curve caused by a change in RI ($\Delta n$) can be characterized either by an angular shift of the curve $\Delta \theta_{res}$ (sensing by angular modulation) or a change in the reflectance $\Delta R$ at a fixed angle (sensing by intensity modulation). The sensitivity with intensity modulation can be estimated by

$$S(\theta) = \lim_{\Delta n \to 0} \frac{\Delta R(\theta)}{\Delta n} = \frac{\partial R(\theta)}{\partial n}.$$  

(3)
To compare the sensitivities of different types of sensors, it is convenient to use the figure of merit (FOM) for the sensitivity by intensity given as

\[ \text{FOM} = \max_{\theta} |S(\theta)|, \]

which is a maximum value of the sensitivity by intensity. \( \Delta n \) as small as \( 1 \times 10^{-3} \) is sufficient to produce the change \( \Delta R_{\text{max}} = 0.12 \) [the maximum value in the inset of Fig. 5(b)]. The ratio \( \Delta R_{\text{max}} / \Delta n \) is 120 RIU\(^{-1}\) for the graphene-based sensor. These values suggest qualitatively that the present sensor offers an extremely high sensitivity by intensity relative to that of the conventional SPR sensor, which has a typical value of \( \Delta R_{\text{max}} / \Delta n \approx 35 \text{ RIU}^{-1}. \)

The reflective spectra in accordance with the number of graphene layers and the incidence angle are illustrated in Fig. 6. Distinctly, the resonant angle changes when two, three, four, five, and six layers are added, and each time it increases when the bandwidth slightly broadens. The sensitivity decreases as the number of nanolayers increases because the nonzero imaginary dielectric constant of graphene induces the damping of EM waves. Also, the FWHM is directly proportional to the damping. The detection accuracy is directly proportional to the shift in resonance angle and inversely proportional to the FWHM. The detection accuracy indicates the ratio of the shift in resonance angle to the FWHM. It is concluded that the detection accuracy decreases as the number of graphene layers increases in the structure. Graphene is highly sensitive to the charged analytes, and its strong interaction capability with light has led to new conceptual SPR biosensors.\(^{25}\)

In conclusion, we present the concept of a prism-waveguide coupling system and its application to the enhancement of graphene monolayer’s absorption in the Vis range. The effects of geometric parameter variations are analyzed and it is shown that the optical absorption can be enhanced to 100\%. The spectra of the graphene absorber are highly sensitive to the RI of the environmental dielectric. The sensitivity by intensity is calculated as 120 RIU\(^{-1}\), which is much higher than that of the conventional SPR sensor. The research achievements reveal the potential implementation of absorbers for graphene in novel optoelectronic devices, and provide a guide to design related nanostructures and devices.

Acknowledgment

This work was supported by the National Science Foundation of China (NSFC) (61203211, 41675154, and 41675133), the Six Major Talent Peak Expert of Jiangsu Province (2015-XXRJ-014), and the Natural Science Foundation of Jiangsu Province (BK20141480, BK20141483, and BE20150003-4).

Fig. 6. Variation of detection spectrum as a function of number of graphene layers. The other parameters are the same as those in Fig. 5(b).